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Abstract *We investigate the cascadability of a microcavity-saturable-absorber-based phase-preserving amplitude regenerator for RZ-DPSK signals. The results show that the tolerance of phase-encoded signals to nonlinear phase noise is increased. A distance improvement ratio up to 1.6 is experimentally demonstrated.*

Introduction

The differential phase-shift keying (DPSK) modulation format has recently attracted much attention for high-speed and ultra long-haul optical transmission. It offers, for instance, a 3-dB improvement in receiver sensitivity compared to OOK (with balanced detection) and an enhanced tolerance to dispersion and nonlinear effects[1].

All-optical regeneration that aims to enhance the signal quality would be attractive to improve the performance of DPSK systems. In the literature, some interesting solutions for phase regeneration based on phase-sensitive interferometric techniques have been proposed[2,3]. However, those techniques are rather complex, and have instability issues. Another approach consists in phase-preserving amplitude regeneration that can prevent the accumulation of nonlinear phase noise (NLPN) during transmission[4]. The cascadability of the phase-preserving amplitude regenerators based on four-wave mixing in fibre[5] and on nonlinear amplifier loop mirror[6] are experimentally demonstrated in the literature. Both use shot-pulse RZ DPSK signals at 10 Gbit/s.

Recently, we have shown that a novel microcavity saturable absorber (SA1)[7] can provide phase-preserving amplitude noise reduction, and therefore, can prevent from the accumulation of NLPN in a RZ DPSK transmission system[8]. The microcavity saturable absorber consists of a passive nonlinear mirror which promises a simple, compact and WDM compatible solution[9].

In this paper, we report on the cascadability assessment of the SA1 based phase-preserving amplitude regenerator in a recirculating loop using conventional RZ33 DPSK at 42.7 Gbit/s. The numerical and experimental results demonstrate that the tolerance of phase-encoded signals to NLPN is considerably increased thanks to the regenerator. An improvement of bit error rate and of transmission distance can be achieved.

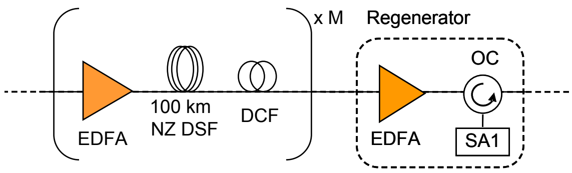

Fig. 1: Scheme of a regenerated transmission.

Numerical simulation

For a complete regeneration of DPSK signals, both phase and amplitude regenerations are needed. However, we illustrate in this section that when SA1 based phase-preserving amplitude regenerators are used in the transmission line, a reduction of SPM-induced NLPN at the receiver can be obtained. Indeed, by strongly reducing the amplitude noise, the SA1 prevents the accumulation of NLPN in the next transmission spans.

The transmission link is modelled as the concatenation of 100 km amplification spans composed of non-zero dispersion-shifted fibres (NZ DSF) followed by a dispersion-compensating-fiber (DCF) (Fig. 1). The NZ DSF has a dispersion of 4.5 $ps.nm^{-1}.km^{-1}$, a nonlinear coefficient of 2 $W^{-1}.km^{-1}$, and an attenuation of 0.23 dB/km. The total span loss is 26 dB, which is compensated for by an EDFA with noise figure of 4.5 dB. The chromatic dispersion is perfectly compensated, and the nonlinearities occur only in the transmission fibre. A phase-preserving amplitude regenerator based on SA1 is inserted every M spans.

The SA1 model is based on the same rate equation as for the classical saturable absorber[10] but with an inverted sign of the last term (which is directly dependent on the input power) in order to obtain a decreasing reflectance in response to an

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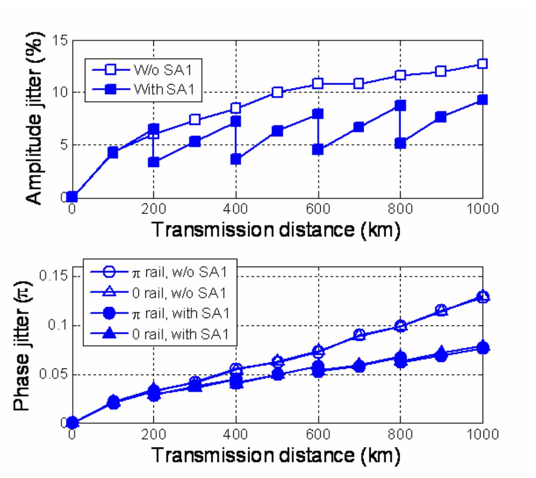

Fig. 2: Amplitude and phase jitter vs. transmission distance with and without SA1.

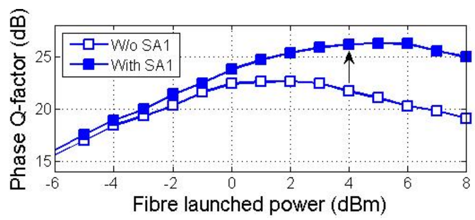

Fig. 3: Phase Q-factor after 1000 km of transmission vs. fibre launched power.

increasing input power:

$$\frac{d\alpha(t,P)}{dt} = \frac{\alpha_0 - \alpha(t,P)}{\tau} + \frac{\alpha P}{\tau P_{sat}}$$

P is the input power, α is the device's absorption, α_0 is the small signal absorption, P_{sat} is the saturation power, and τ is the recovery time. The parameters used in the simulation are P_{sat}=7 mW, τ=3.5 ps and α_0=5.3, where d is the total quantum-well section thickness. Those parameters are representative of the investigated device for the experimental studies.

The rms variations of the amplitude and differential phase (on the zero and π rails) for RZ DPSK signals transmitted through the system in the cases with and without SA1-based amplitude regenerators are plotted in Fig. 2. The fibre launched power is set at 4 dBm. The regenerators are located after every 200 km of transmission. As can be seen, in the absence of regenerators, both the amplitude and phase jitters increase continuously which can become critical for the system performance. In the case with regenerators, the amplitude noise is considerably reduced at each regenerator location. After the first regenerator, the slope of differential phase jitters with transmission distance is reduced. At 1000 km, the rms phase jitter is reduced by 40% compared to the non regenerated case.

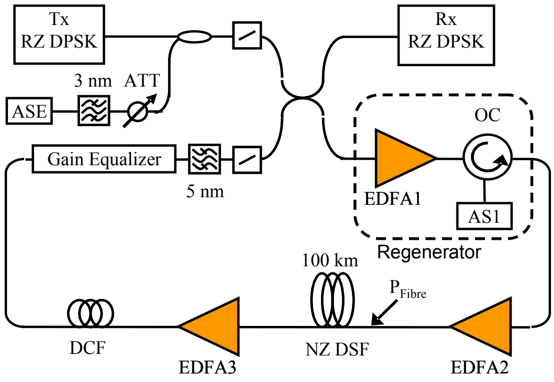

Fig. 4: Recirculating loop experiment of cascaded microcavity-saturable-absorber-based regenerator.

As a qualitative estimate of the transmission performance of the system, we use here the differential phase Q-factor (defined as π divided by the sum of the rms variations of the differential phase between adjacent bits on the zero and π rails)[11], which provides a measure of the phase fluctuation in the signal. Fig. 3 shows the phase Q-factor in dB (20.log10(Q)) after 1000 km of transmission with and without SA1 versus fibre launched power. In the linear regime at low fibre launched power, the system performance is limited by OSNR degradation. No improvement by the regenerator is observed, as it preserves the signal phase. At high fibre launched power, Q-factor is improved. An increase of nonlinear tolerance is thus obtained thanks to the regenerator. This Q-factor margin can be used for increasing the transmission distance, which will be demonstrated experimentally in the next sections.

Experimental setup

The experimental setup is shown in Fig. 4. The transmitter based on Mach-Zehnder modulators generates an 8-ps-pulse-width RZ DPSK signal at 42.7 Gbit/s. The signal wavelength is centred at 1550 nm. An ASE source followed by a 3-nm band-pass optical filter, followed by a variable optical attenuator (ATT) is used in order to modify the OSNR at the transmitter output.

The signal is boosted by EDFA1 before being sent to SA1 via an optical circulator (OC). The transmission line consists of 100 km of non-zero dispersion-shifted fibre (NZ DSF) with chromatic dispersion of 4.5 ps/km/nm at 1550 nm, followed by a dispersion-compensating fibre (DCF). EDFA2 increases the launched power up to 13 dBm, while EDFA3 compensates for the residual loss. A gain equalizer is required to compensate the signal spectrum distortion due to the device's resonance. The preamplified RZ DPSK receiver consists of a fibre-based delay-line interferometer (DLI) and a balanced detector.

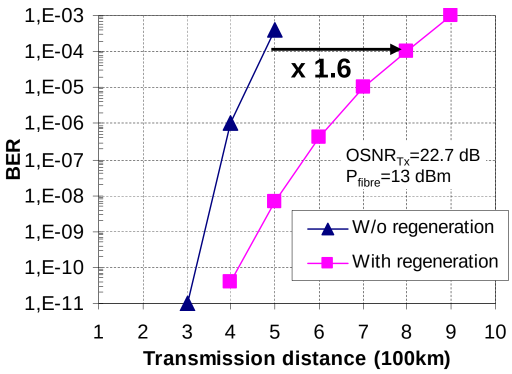

Fig. 5: BER vs. transmission distance.

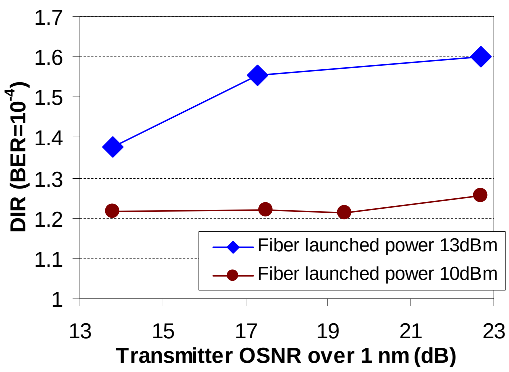

Fig. 6: Distance improvement ratio at BER of 10^{-4} with different fibre launched powers and transmitter OSNR.

Experimental results

Figure 5 shows the measured bit error rate (BER) versus transmission distance with and without SA1 based amplitude regeneration. The OSNR at the transmitter (called OSNR$_{Tx}$) is 22.7 dB (over 1 nm) and the fibre launched power is 13 dBm. This high value is unrealistic, but is required, in our experiment, to generate a high enough amount of NLPN in 100 km of transmission fibre. For longer distance between regenerators, the BER curves are shifted towards lower input power values since less launched power is needed for the same amount of total nonlinear phase noise in the system. In the case without SA1, the BER grows rapidly due to linear and nonlinear phase noise accumulation. When the phase-preserving amplitude regenerator is applied, the amplitude noise is reduced and the nonlinear phase noise is partly removed. As a consequence, the transmission distance is enhanced thanks to the regenerator. A transmission distance of 800 km is reached for a BER of 10^{-4} compared to 500 km in the case without regeneration, a distance improvement ratio of 1.6 is thus obtained.

We define the distance improvement ratio (DIR) as the ratio of distances covered with and without regeneration for a given BER. Fig. 6 presents the evolution of DIR versus OSNR$_{Tx}$ for a BER of 10^{-4} and with fibre launched powers of 10 dBm and 13 dBm. At the first glance, the results show that the DIR generally exceeds 1.2 for all OSNR$_{Tx}$ values. As can be seen, a difference in regeneration efficiency is shown when the fibre launched power varies from 10 dBm to 13 dBm. This can be explained by the fact that, at higher fibre launched power (13 dBm), the nonlinear effects that convert amplitude noise into phase noise are more efficient. Consequently, better regenerator efficiency is obtained (distance improvement ratio of 1.4 to 1.6 compared to 1.2 at 10 dBm). The greater the fibre launched power, the more efficient the nonlinear effects, and the better the distance improvement.

When OSNR$_{Tx}$ increases the obtained DIR is slightly better. For a fibre launched power of 13 dBm, a DIR of 1.4 is obtained at low OSNR$_{Tx}$ (13.8 dB), and this improvement ratio is 1.6 at high OSNR$_{Tx}$ (22.7 dB). At a fibre launched power of 10 dBm, this evolution is less visible because the nonlinear effects are less efficient.

Conclusions

Cascaded performance of a phase-preserving amplitude regenerator based on a microcavity saturable absorber has been numerically and experimentally investigated in a RZ-DPSK transmission system at 42.7 Gbit/s via a recirculating loop setup. The obtained results show that the regenerator reduced the amplitude noise, which is the origin of nonlinear phase noise, thus improve the system performance. The best regenerator efficiency is achieved at high fibre launched power where the nonlinear effects are significant. A distance improvement ratio up to 1.6 is experimentally obtained at bit error rate of 10^{-4}.

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